

# A Very Radio-Loud Narrow-Line Seyfert 1: PKS 2004-447

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## ABSTRACT

We have discovered a very radio-loud Narrow-Line Seyfert 1 candidate: PKS 2004-447. This Seyfert is consistent with the formal definition for NLS1s, although it does not have quite the same spectral features as some typical members of this subclass. Only ROSAT survey data is available at X-ray wavelengths, so it has not been possible to compare this source with other NLS1s at these wavelengths. A full comparison of this source with other members of the subclass will improve our physical understanding of NLS1s. In addition, using standard calculations, we estimate the central black hole to have a mass of  $\sim 5 \times 10^6 M_\odot$ . This does not agree with predictions in the literature, that radio-loud AGN host very massive black holes.

*Subject headings:* galaxies:active — galaxies:Seyfert — quasars:individual(PKS 2004-447)

## 1. Introduction

The radio-loud source PKS 2004-447,  $z = 0.24$ , was identified as a candidate Narrow-Line Seyfert 1 (NLS1) from low resolution optical spectra of a subsample of quasars identified

in the Parkes Half-Jansky Flat-Spectrum Sample (Drinkwater et al. 1997)(hereafter PHFS). The PHFS is designed to efficiently select radio-loud AGN by looking for flat or inverted radio spectra over the range of 2.7 and 5.0 GHz. It contains 323 radio bright ( $> 0.5\text{Jy}$  at 2.7 GHz), generally compact radio sources. Higher resolution spectroscopy of this object was obtained giving more accurate velocity widths of the emission lines indicating this may be an NLS1 but more accurate spectroscopy is still needed to be able to clearly separate the broad and narrow components of  $\text{H}\beta$ . In any case this object has very interesting implications to the study of AGN.

NLS1s are generally considered to be an extreme but common subclass of AGN. They are defined by their optical emission line properties, such that the  $\text{H}\beta$  line is both strong (with a flux ratio  $[\text{O III}]/\text{H}\beta < 3$ , similar to Seyfert 1 galaxies) and narrow (the  $\text{H}\beta_{FWHM} < 2000\text{km s}^{-1}$ ) (Osterbrock and Pogge 1985). These properties are correlated with strong Fe II emission and a strong soft X-ray excess, amongst other properties, for most objects in the subclass. NLS1s do not appear to form a distinct class but are instead connected to the “standard” broad-line Seyfert population through a continuum of properties. Boroson and Green (1992) have shown that NLS1s cluster at one end of the region defined by the first principal component described in their study of the optical spectra of 87 low-redshift BQS quasars. The first principal component is thought to describe the major physical property in quasar structure that is responsible for spectral differences between AGN, independent of orientation. Boroson and Green (1992) suggest that the physical parameter driving this eigenvector is  $\dot{M}/\dot{M}_{Edd}$ , where  $\dot{M}$  is the rate of mass accretion onto the central massive object. NLS1s are thought to be accreting at a rate closer to the Eddington limit ( $\dot{M}_{Edd}$ ) (Boroson and Green 1992; Laor et al. 1997). NLS1s are generally radio-quiet objects, with only three previously identified radio-loud objects, PKS 0558-504 (Remillard et al. 1986), RGB J0044+193 (Siebert et al. 1999) and J0134.2-4258 (Grupe, Leighly, Thomas, & Laurent-Muehleisen 2000). Boroson and Green (1992) find that radio-loud QSOs and the NLS1s (with a strong, soft X-ray excess) lie at opposite ends of the primary eigenvector.

Although the criteria for NLS1s are well defined, it is unclear whether these phenomenological attributes reflect a single underlying physical mechanism. Thus the discovery of a very radio-loud NLS1 may indicate that the observational definition of NLS1s requires refinement. Alternatively, radio-loud NLS1s may provide a more stringent test of the models of NLS1s. Three important consequences of the identification of a radio-loud NLS1 will be considered. Firstly, are the radio-loud NLS1s the same class of objects as most others in the class. Secondly, are radio-loud NLS1s consistent with any of the popular models for NLS1s and thirdly, do radio-loud quasars require large mass black holes. This object challenges that assertion as is further discussed in section 4

In section 2, we present the observational data on PKS 2004-477. In section 3, this object is compared to the three other radio-loud NLS1s which have been identified. The central black hole mass is determined using standard techniques in section 4, and possible models for NLS1s are discussed in section 5. Finally our conclusions are presented in section 6.

## 2. Observational Data

### 2.1. Optical Spectrum

PKS 2004-447 was first identified as a NLS1 candidate from a low resolution spectrum obtained using the RGO/FORS spectrograph at the AAT in 1984 and published in Drinkwater et al. (1997). A higher resolution confirmation spectrum was taken using the double beam spectrograph (DBS) on the ANU 2.3m telescope, 1st August 2000, and is shown in Fig 1. The conditions were not photometric. The spectrum was reduced using standard procedures in the IRAF. The spectrum has a resolution of  $\sim 2.2\text{\AA}$ .

Typically, in NLS1s, Fe II emission contaminates the spectrum making accurate measurements of  $H\beta$  and [O III] difficult. In order to account for this and to get an estimate on the strength of the Fe II emission in this object we employed the Fe II subtraction method introduced by Boroson and Green (1992) and now commonly used. We use a template Fe II spectrum taken from the prototype strong Fe emitter I Zw 1 and scale it and shift it until the width and intensity match those seen in our object. We did this over the region 5050-5500 $\text{\AA}$  using a  $\chi^2$ -minimisation to get the best value for the scaling. We find that this spectral region contains very little Fe II emission with an equivalent width  $EW < 10\text{\AA}$  for the whole Fe II complex in the region 5050-5450  $\text{\AA}$ . Compared to values measured in Boroson and Green (1992), this is extremely low (although we are fitting a slightly different region of the Fe II spectrum). We measured the line widths and fluxes using Lorentzian fits to the emission lines and the results are summarised in Table 1. The width of  $H\beta_{FWHM} = 1447\text{km s}^{-1}$  and the flux ratio  $[\text{O III}]/H\beta = 1.6$ , fit the criteria for classification as a NLS1. The DBS spectrum does not extend to wavelengths of the Fe II( $\lambda 4570$ ) lines. However the previous low resolution spectrum indicates Fe II emission in the region 4435-4700  $\text{\AA}$ , blueward of the  $H\beta$  line (Fig 2). The low resolution spectrum also shows strong  $H\alpha$  and evidence for  $H\gamma$  emission and it also indicates that the strength of the  $H\beta$  emission, relative to [O III] has varied between the two epochs.

PKS 2004-447 is also optically variable. The magnitude of this object measured from the COSMOS/UKST Southern Sky Catalogue is  $B_J = 18.1$ , while more recent photometry

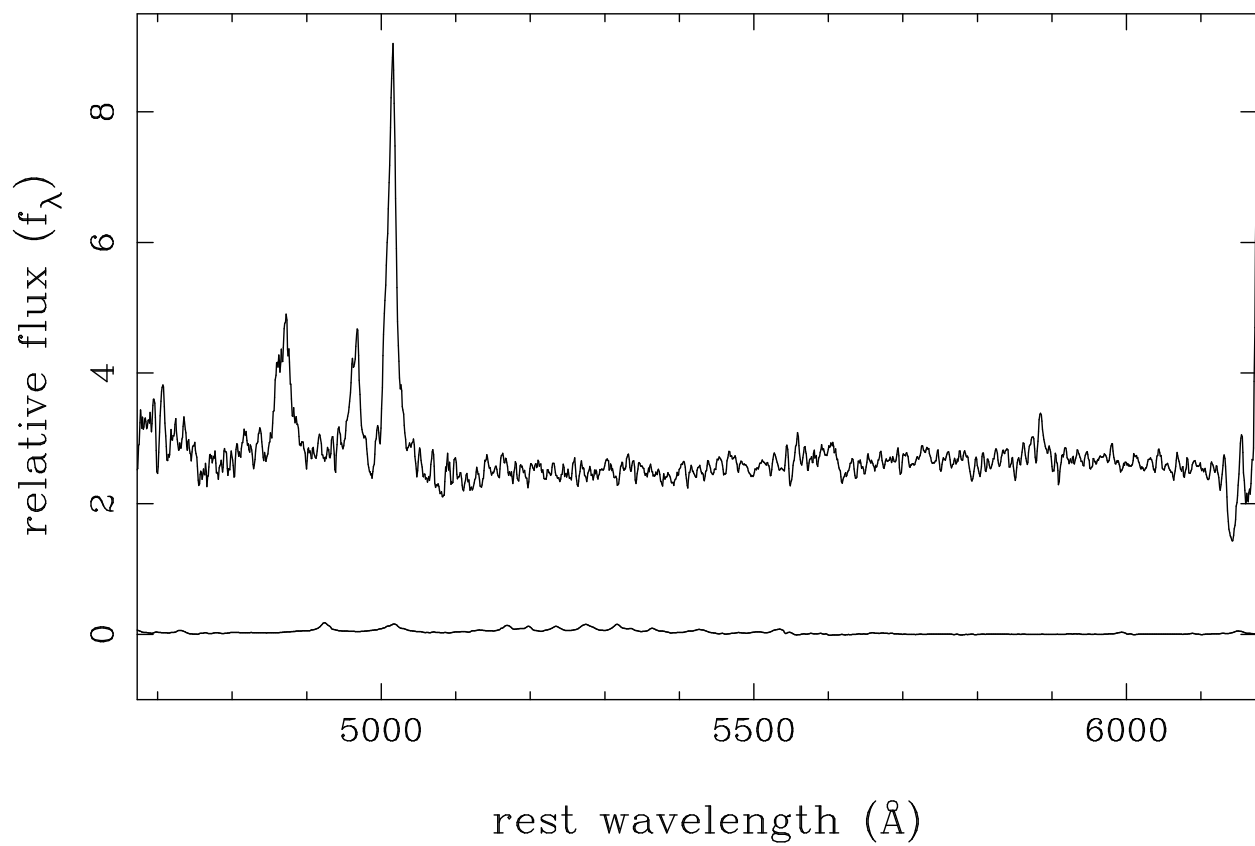


Fig. 1.— Rest frame, medium resolution spectrum of PKS 2004-447 from the DBS on the 2.3m telescope at the Siding Springs Observatory, showing the  $H\beta$  and  $[O\ III]$  region (top) and the best-fit rescaled Fe II spectrum shown below it.

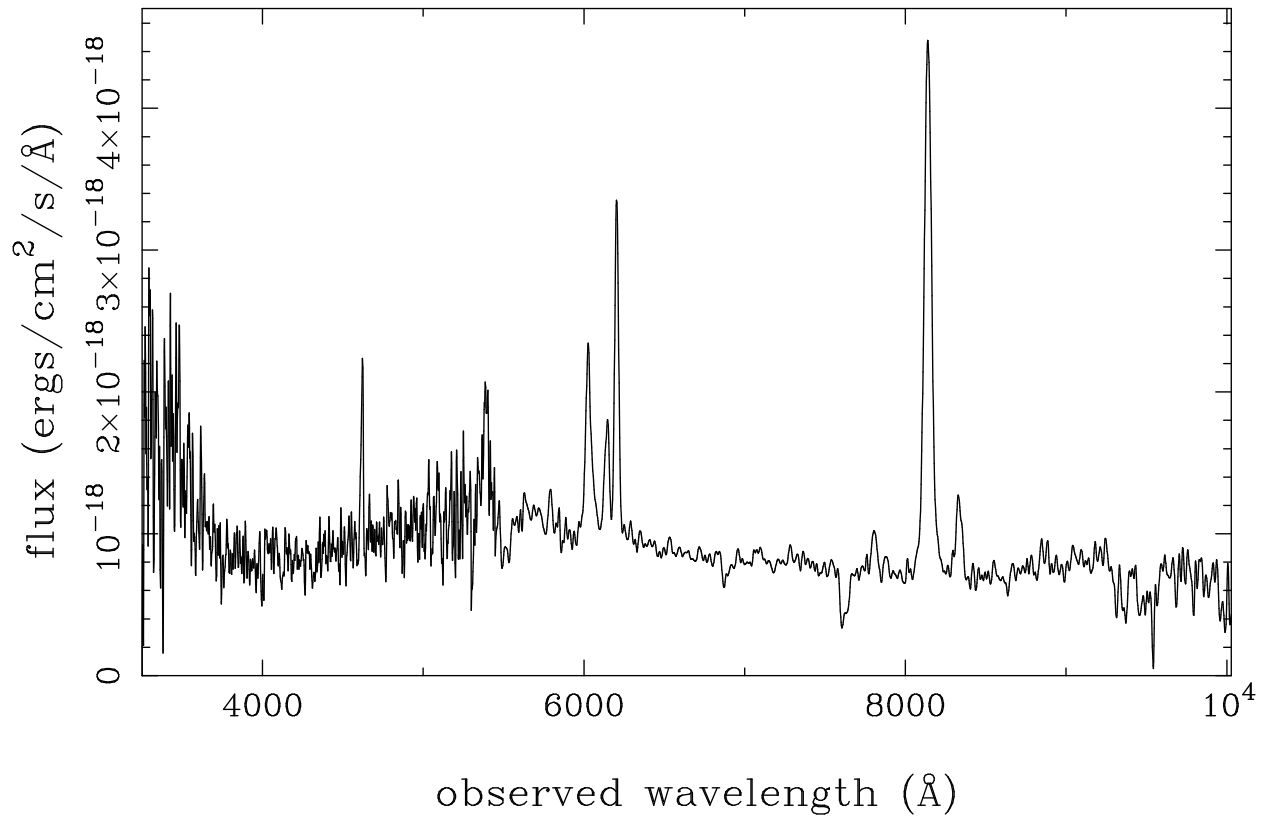


Fig. 2.— Low resolution spectrum of PKS 2004-447 from RGO spectrograph on the AAT.

obtained on the ANU 2.3m telescope gave  $B = 19.5$  (Francis, Whiting, & Webster 2000), indicating a drop in flux by a factor of  $\approx 4$  over an interval of several years. Simultaneous optical/IR photometry are shown in Fig 3. The continuum is very red and there is no evidence of a big blue bump. The absolute magnitude is between -19.0 and -21.2, for  $q_0 = 0.5$  and  $H_0 = 100$ , clearly placing this in the Seyfert luminosity class.

## 2.2. Radio Emission

Under the selection criteria, the PHFS objects are detected above 0.5 Jy at 2.7GHz and with a spectral slope  $\alpha < 0.5$  ( $F_\nu \propto \nu^{-\alpha}$ ) taken from non-simultaneous observations at 2.7GHz and 5.0 GHz. Using this method PKS 2004-447 had a 2.7 GHz flux of 0.81 Jy and a spectral index  $\alpha_r = 0.36$ . Subsequent simultaneous observations of this source were taken using the ATCA (23rd November 1995) and the radio flux had varied since the Parkes observations, demonstrating long term variability at these frequencies as well. The radio spectrum is shown in Fig 3. A powerlaw fit to the simultaneous data gives a spectral index  $\alpha_r = 0.67$ ; thus PKS 2004-447 is actually a steep spectrum source. Calculating  $R$ , where  $R$  is the ratio of radio to optical flux ( $f_{4.85\text{GHz}}/f_B$ ), (Kellerman et al. 1989), gives values in the range  $1710 < R < 6320$  depending on value used for the optical magnitude. Obviously, this source is very radio-loud.

The radio image is unresolved in the ATCA observations. The visibility of PKS 2004-477 was measured using the Parkes-Tidbinbilla Interferometer on a 275 km baseline at 2.3 GHz (Duncan et al. 1993). The average of two measurements gave a visibility of 0.680 corresponding to an angular size of  $\sim 0.036''$  or  $\sim 85pc$ . Since this source size is derived from a 2-element interferometer, it is measured along one baseline.

There are two previous studies of the radio properties of NLS1s. The most recent and

Table 1: Equivalent widths of the emission lines<sup>a</sup>

	H $\beta$ (4861)	O III (4959)	O III (5007)
FWHM(km s <sup>-1</sup> )	1447	951	754
flux relative to H $\beta$	1.0	0.61	1.61
EW (Å)	31.6	19.6	50.6
Offset (km s <sup>-1</sup> )	+28	-78	0

<sup>a</sup>Measured from the spectrum in Fig 1; details are described in the text.

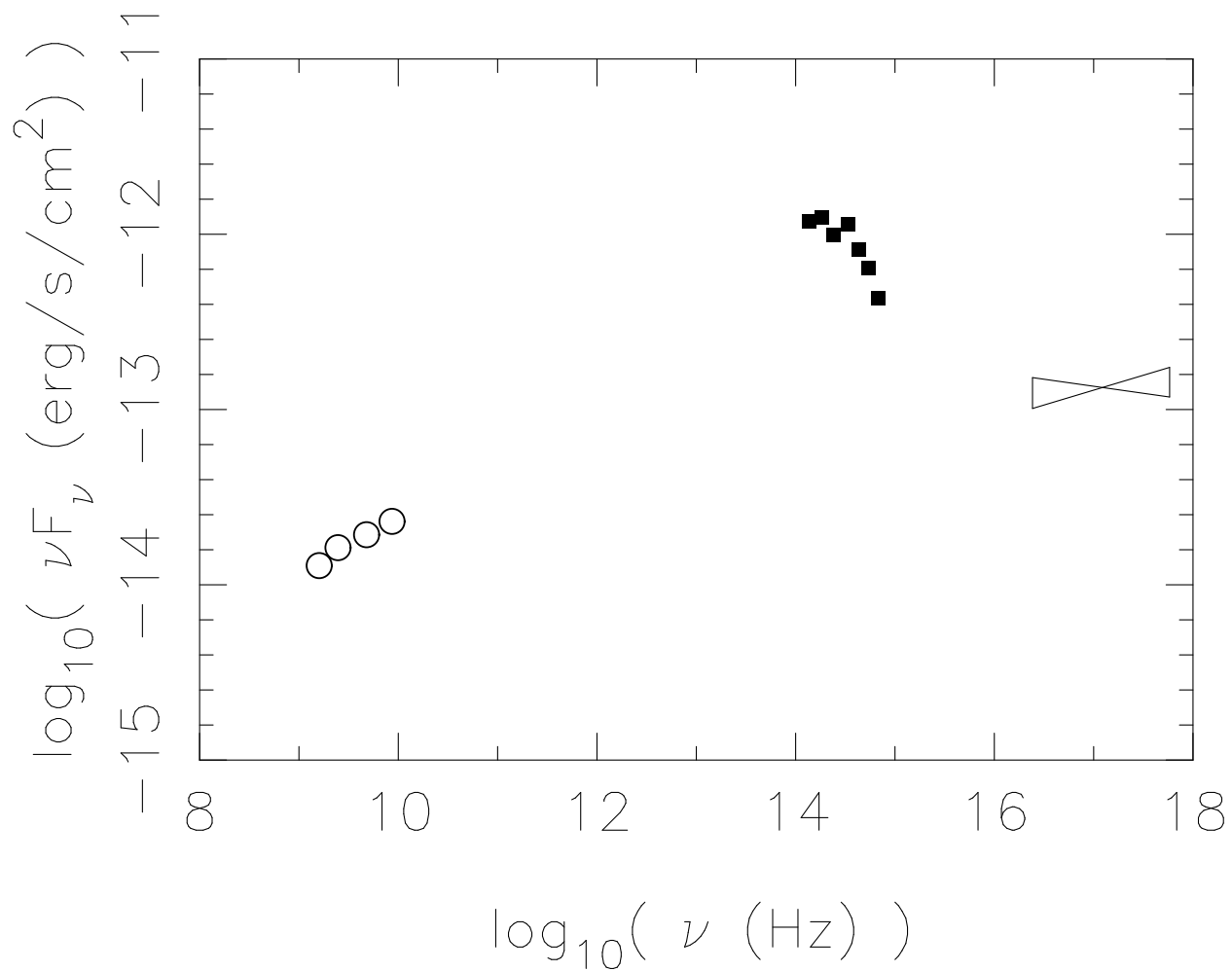


Fig. 3.— Spectral energy distribution of PKS 2004-447. Radio data from contemporaneous observations at the ATCA (circles, unpublished data). Optical data from quasi-simultaneous observation at Siding Spring (Francis, Whiting, & Webster 2000, squares). X-ray data from ROSAT All Sky Survey (Siebert et al. 1998, line).

well defined is that of Moran (2000), who obtained high resolution observations of 24 NLS1s at 20cm and 3.6cm using the VLA. All but one of the sources were detected, with 20cm fluxes up to  $10^{25} W Hz^{-1}$ , which is higher, on average, than classical Seyferts. Moran found most NLS1s unresolved at  $\sim 1''$ , with generally quite steep ( $\alpha \approx 1.1 - 1.2$ ) radio spectra, though the spectral index of PKS 2004-477 is consistent with the flattest values. In other words these could be considered as low luminosity compact steep spectrum (CSS) sources. There is also a few cases of variability at 20cm, again, as seen in PKS 2004-477. Thus PKS 2004-477 is compact, steep-spectrum and variable in the radio, which are similar properties to other NLS1s Moran (2000). This is further discussed in section 5.

### 2.3. X-ray Emission

NLS1s have unusual X-ray properties. They generally display a large soft X-ray excess, a steep hard X-ray spectrum and large amplitude X-ray variability over short and long timescales. Siebert et al. (1998) investigated the X-ray properties of the PHFS using the ROSAT All Sky Survey. PKS 2004-447 was detected with a total flux in the 0.1-2.4 keV range of  $0.427 \pm 0.218 \times 10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1}$  corresponding to  $L_X = 2.9 \times 10^{43} \text{ erg s}^{-1}$ . We find an optical-to-X-ray slope of  $\alpha_{ox} = -1.2$ . This is consistent with values found by Xu, Wei & Hu (1999) for a ROSAT selected sample of NLS1s.

## 3. Previous Detections of Radio-Loud NLS1s

Most NLS1s are radio-quiet and only three radio-loud NLS1s are known (Siebert et al. 1999). PKS 0558-504 was optically identified on the basis of X-ray positions from the High Energy Astronomical Observatory (Remillard et al. 1986). It was noted as not only having very narrow hydrogen emission lines, but also strong Fe II emission. It has a radio flux of 113 mJy at 4.85 GHz, an optical magnitude  $m_B = 14.97$  and a redshift  $z = 0.137$ . This gives  $R \approx 27$  (Siebert et al. 1999). This source exhibits strong X-ray variability on medium (months) and short (days, hours) time scales (Gliozzi et al. 2000) and an X-ray flare indicating relativistic beaming (Remillard et al. 1991).

Siebert et al. (1999) identified RGB J0044+193 as a radio-loud NLS1. RGB J0044+193 has only a moderate radio flux, but is calculated to have a radio-to-optical flux ratio  $R \approx 31$ . It was identified as a radio-loud X-ray source with a redshift of 0.181 in a cross-correlation of the ROSAT All-Sky Survey and the Green Bank 5GHz radio survey (Laurent-Muehleisen et al. 1998). It has the bluest optical spectrum of any NLS1 observed to date. Siebert et



al. (1999) measure an optical continuum slope of  $\alpha = 1.3$  redward of  $5000\text{\AA}$  and a slope of  $-3.1$  blueward of  $5000\text{\AA}$  where  $f_\nu \propto \nu^{-\alpha}$ . This source was detected in the 87GB survey with  $f_{4.85\text{GHz}} = 24$  mJy. A high resolution follow-up using the VLA at 4.85 GHz gave a flux of only 7 mJy (Laurent-Muehleisen et al. 1997), indicating that this source is extended or variable. The latter is supported by the fact that the radio source is unresolved on the VLA map and it is not detected at 1.4 GHz in the NRAO/VLA Sky Survey, which is sensitive down to 2.5 mJy. This suggests that the classification of the source as radio-loud is uncertain. In all other respects, RGB J0044+193 is indistinguishable from radio-quiet NLS1s.

RX J0134.2-4258 was discovered by Grupe, Leighly, Thomas, & Laurent-Muehleisen (2000) to have the steepest soft X-ray spectrum observed during the ROSAT All-Sky Survey. It has an optical magnitude of  $m_V = 16.2$  and  $z = 0.237$ . It was detected in the PMN survey (Wright et al. 1994) with a flux of 0.055 Jy at 4.85 GHz, and was subsequently re-observed at the VLA to have a flux of 0.025 Jy at 8.4 GHz. This gives a ratio of  $R = 71$ , and a radio spectral index of  $\alpha = 1.4$  for non-simultaneous observations. The source is highly variable in the X-ray, and there is evidence for variability at other wavelengths. The Fe II emission is strong, unlike that of PKS 2004-477.

#### 4. Black Hole Mass

There seems to be a growing consensus that a more massive black hole is needed to produce a radio-loud quasar (Laor 2000; Kaspi et al. 2000; McLure and Dunlop 2000; Peterson et al. 2000). PKS 2004-447 appears to directly conflict with this statement. Calculations of the black hole mass rely on the assumption that the dynamics of the BLR gas are dominated by the central black hole. To calculate the black hole mass for this object we use the results of Kaspi et al. (2000), which are derived from a reverberation study of 17 quasars. Kaspi et al. (2000) empirically determine linear relationship between  $R_{BLR}$  and the luminosity ( $\lambda L_\lambda$ ) which we use to estimate the radius of the BLR-emitting gas. From equation 5 in Kaspi et al. (2000).

$$R_{BLR} = (32.9) \left[ \frac{\lambda L_\lambda(5100\text{\AA})}{10^{44}\text{erg s}^{-1}} \right]^{0.700} \text{ lt-days} \quad (1)$$

We use the luminosity taken from a linear interpolation between photometric data points (Francis, Whiting, & Webster 2000) at the rest wavelength of  $5100\text{\AA}$ . Following Kaspi et al. (2000), the mass of the black hole is given by  $M_{BH} = rv^2G^{-1}$ . To determine  $v$ , the velocity, we correct  $v_{FWHM}$  of the  $H\beta$  emission line by a factor of  $\sqrt{3}/2$  to account for velocities in

three dimensions. The mass is then

$$M = 1.464 \times 10^5 \left( \frac{R_{BLR}}{\text{lt-days}} \right) \left( \frac{v_{FWHM}}{10^3 \text{km s}^{-1}} \right)^2 M_{\odot} \quad (2)$$

Using the cosmology  $q_0 = 0.5$  and  $H_0 = 100 \text{km s}^{-1} \text{Mpc}^{-1}$ , this gives us a value for the central black hole mass of  $5.4 \times 10^6 M_{\odot}$ . This mass is two orders of magnitude lower than those obtained by other authors for radio-loud quasars. In a study of the black hole masses of quasars from the Boroson and Green (1992) sample, it was found that all quasars with  $M_{BH} < 3 \times 10^8 M_{\odot}$  are radio-quiet (Laor 2000). The data from this sample is shown in Fig 4, with the mass of PKS 2004-447 added. It can be seen that PKS 2004-447 is quite different than the rest of the sample. We note that Laor (2000) assumes a flatter relationship than Kaspi et al. (2000), but estimates that this difference results in a discrepancy of  $< 50\%$  in the mass estimates. This corresponds to a shift of  $< 0.3$  in  $\log M_{BH}$ , which does not qualitatively affect the result in figure 4. Similarly McLure and Dunlop (2000), in their study of radio-loud and radio-quiet objects, came to the conclusion that a radio-loud quasar requires a mass  $M_{BH} > 6 \times 10^8 M_{\odot}$ . This again, is more than two orders of magnitude greater than the mass we derive for PKS 2004-447.

We speculate that the reason our object has a black hole mass so much smaller than those seen in previous studies is not entirely due to it being an unusual object, but more likely due to the selection criteria in the previous samples. All previous studies have used optical selection to compile their sample. This selection technique preferentially selects radio-loud quasars which are blue with very broad emission lines. However samples of radio-selected quasars such as the PHFS show that the general radio-loud population can be quite different (Webster et al. 1995; Francis, Whiting, & Webster 2000). In these samples it may be quite common to have low mass black holes producing large radio-jets and this issue will be addressed in a future paper.

## 5. Discussion of Physical models

### 5.1. Classification

Since the subclass of NLS1s are defined by phenomenological measurements, rather than a specific physical model, it is possible that more than one physical mechanism will produce the defining parameters. First we should consider whether PKS 2004-447 should be defined as an NLS1. Certainly it meets the formal definition of Osterbrock and Pogge (1985). In the X-ray, the flux ratios are consistent with other NLS1s, but pointed observations are required to obtain spectral information. In the optical, the Fe II emission is much weaker than other

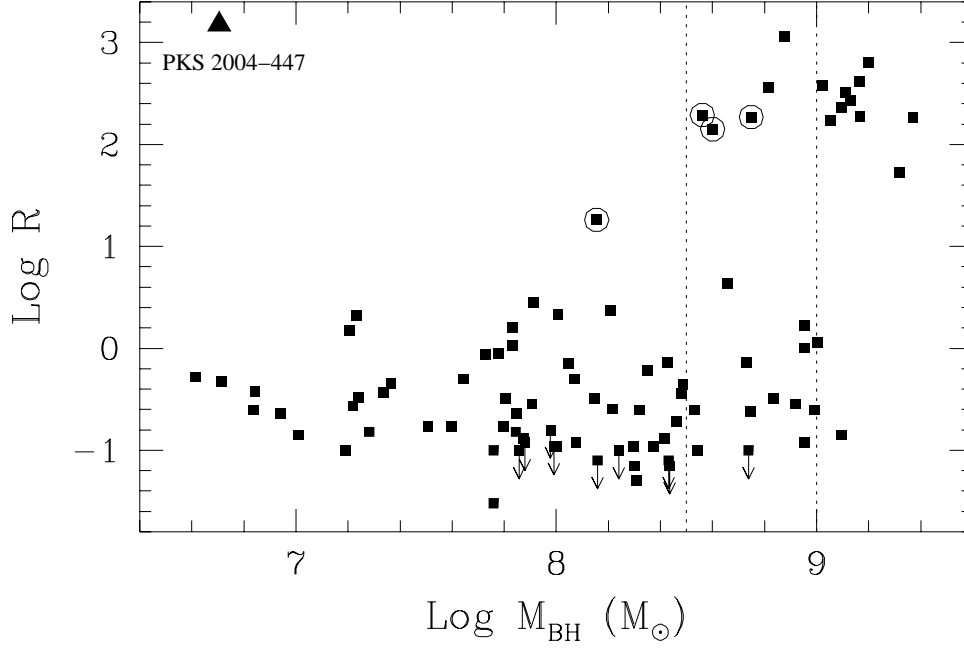


Fig. 4.— Radio loudness vs. black hole mass, showing PKS 2004-447 in relation to data from figure 2 of (Laor 2000). The Laor (2000) data points are from the Boroson and Green (1992) sample of 87 low redshift quasars. The circled squares were proposed by Falcke, Patnaik, & Sherwood (1996); Falcke, Sherwood, & Patnaik (1996) to be beamed intrinsically radio-quiet quasars. PKS 2004-447 has been placed on the diagram at its lowest value for  $R$  quoted in text.

NLS1s. Apart from the obvious strength of the radio flux, the size of the radio source, and its spectral index are consistent with other radio measurements (Moran 2000).

The object’s radio properties fit with the definition of a Compact Steep Spectrum radio source (CSS) according to the definition from Fanti et al. (1995) of:  $P_{tot} > 10^{26} \text{W Hz}^{-1}$ ; a size smaller or comparable to the optical galaxy scale; and the spectral index  $\alpha_r > 0.5$ . The CSS sources tend to have spectra with narrow emission lines typical of radio-galaxies. The broad component of  $\text{H}\beta$  seems to be extremely weak or absent (Morganti 1997). Gelderman and Whittle (1994) find an average value  $[\text{O III}]/\text{H}\beta \sim 5$  indicating that the  $\text{H}\beta$  flux is too weak to be an NLS1. In the study of Gelderman and Whittle (1994) all CSS sources with measurable  $\text{H}\beta$  are of quasar luminosity. So PKS 2004-447 is unusual in both categories: firstly it has an optical spectrum which is unusual for CSS source; and secondly has radio power unusual for NLS1s.

The source is clearly in the Seyfert luminosity range, as are a significant fraction of the sources in PHFS. The differences in optical spectral properties, (such as the weakness of the Fe II emission) between PKS 2004-477 and NLS1s in general raise the possibility that the NLS1-defining characteristics of this source are due to a different physical mechanism from other objects in the subclass. This possibility may be resolved when an X-ray spectrum is obtained.

## 5.2. Physical Models

Finding unusual objects in a particular class is a useful method for distinguishing between different possible physical models. Although there have been a variety of physical models suggested for NLS1s (Taniguchi et al. 1999, see for a summary) it seems that the model with the strongest observational support is the high accretion rate, low black hole mass model. This model suggests that NLS1s are objects where the black hole is accreting at a rate closer to the Eddington limit compared to broad-line Seyferts. Since there is a higher rate of accretion, a given luminosity corresponds to a black hole with a smaller mass. If the size of the BLR is determined by the bolometric luminosity, then, at a given radius, the broad line clouds will have slower velocities and the emission lines will be narrower. This model was developed to explain the soft X-ray excess and the steep X-ray powerlaw, by analogy with the X-ray spectra of galactic black hole candidates accreting in their “high” state (Pounds et al. 1995). For high accretion rates, the soft thermal emission from the disk becomes energetically dominant, producing the soft X-ray excess, and the X-ray powerlaw spectrum can be steepened as a result of Compton cooling of the electrons by the soft X-ray photons.

An alternative model for the narrow Hydrogen lines suggests we are viewing the source near the axis of the accretion disk. If the velocity width of the Hydrogen emission lines is dominated by the rotation of the accretion disk, then they will appear narrow. The radio emission in PKS is moderately steep spectrum, which weakens the argument that we observe this source near the axis. Indeed it also weakens arguments which suggest that the radio emission is strongly boosted by beaming. However the radio source is very compact, with no evidence at any frequency for double-lobed emission.

## 6. Conclusion

PKS 2004-447, detected in the PHFS, is an unusual source. To summarize the major points regarding PKS 2004-447:

1. It has  $H\beta$  width and strength consistent with being classified as an NLS1 as defined by Osterbrock and Pogge (1985).
2. Its radio properties are very unusual for a Seyfert Galaxy having the following characteristics: very strong radio flux, 0.81 Jy at 2.7 GHz; very radio-loud,  $R > 1700$ ; steep radio spectral index  $\alpha_r = 0.67$ ; compact radio source; some evidence of long term variability. These properties are consistent with it being classified as a Compact Steep Spectrum source.
3. It has been detected in the RASS with a flux  $0.427 \times 10^{-12}$  erg cm $^{-2}$  s $^{-1}$  but no spectral information is available.
4. Following the procedure set out by Kaspi et al. (2000), we calculate the black hole mass to be  $5.4 \times 10^6 M_\odot$ . This mass is more than 2 orders of magnitude lower than those seen previously for radio-loud AGN and challenges previous results that a large black hole mass is needed to produce radio-loud AGN.

Additional observations of the X-ray spectrum will further constrain models and may provide evidence that the black hole is accreting at a rate closer to the Eddington limit. This would be an indication that the underlying physical mechanism in this object is similar to those in other NLS1s, and that the radio power of the object is actually connected to a different parameter.

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